Atmospheric Research 203 (2018) 95–104

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Elevated heat pump effects of dust aerosol over Northwestern China during summer

Yaoguo Tang[a], Yongxiang Han[a,b,*], Xiaoyan Ma[a,b], Zhaohuan Liu[a]

[a] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China

[b] Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science & Technology, Nanjing 210044, China

ARTICLE INFO

Keywords:
Dust aerosols
Elevated heat pump effect
Monsoon
Northwestern China
WRF-Chem

ABSTRACT

The Elevated Heat Pump (EHP) effect demonstrates a significant interaction between the aerosol climatic effect and the monsoon, both are important for climate research. In Northwestern China, the influence of EHP mechanism is still lacking in research. In this study, the EHP effects in Northwestern China are investigated by three sensitivity tests using a WRF-Chem model coupled with the Shao dust emission scheme. Results show that: 1) the anomalous circulation caused by dust aerosols are proved to the existence of EHP effect in Northwestern China; 2) three updrafts over the desert are transported eastward at high altitude and subside in Northeastern China, forming a complete secondary circulation with low-level easterly flow from Badain Jaran and Tengger to Taklimakan; 3) a northeasternerly anomaly flow from Northeastern China can affect the intensity of East Asian summer monsoon (EASM), and increase precipitation in the middle and lower reaches of the Yangtze River and decrease precipitation in Northeastern China. 4) We present a conceptual model of EHP in Northwestern China to provide a better understanding of the climatic effects of dust aerosols.

1. Introduction

Dust aerosol is an important component of natural aerosols. It can directly influence the radiation budget of Earth-atmosphere system by scattering and absorbing radiation and indirectly modify cloud microphysical properties through aerosol indirect effect (AIE) (Twomey et al., 1984; Albrecht, 1989; Huang et al., 2006). Additionally, the “iron fertilizer effect” of dust aerosols can also affect the growth of marine organisms and consequently lead to a decrease of CO_2 and global cooling (Ridgwell, 2002). Research shows the dust aerosol accounts for about 30% of global aerosol optical thickness, which highly emphasizes the vital role of dust aerosol in linking atmosphere, biosphere and lithosphere, and therefore, making it a key factor of global mass circulation and climate change (Perlwitz et al., 2001; Wang et al., 2015). Different from radiative forcing of greenhouse gases, aerosol radiative forcing is deemed to be particularly important at a regional scale due to relatively short lifetime. Dust aerosols affect atmospheric energy budget by scattering or absorbing solar radiation along with absorbing surface long-wave radiation, in turns decreasing solar radiation reception at surface and lower atmosphere (Lau and Kim, 2006; Solmon et al., 2008; Han et al., 2012).

Lau et al. (Lau and Kim, 2006; Lau et al., 2006, 2008) proposed an Elevated Heat Pump (EHP) hypothesis to reveal the interaction between aerosol climatic effects and Indian summer monsoon. This EHP hypothesis suggests dust and black carbon are stacked up against the south slope of the Tibetan Plateau and heats the mid-to-upper troposphere over the Plateau during the pre-monsoon period, which usually induces ascending motion in lower troposphere and drawing in moist warm air over the Indian subcontinent, strengthening of Indian monsoon rainfall.

The EHP hypothesis has raised great interest in scholars. Series of research have appeared to confirm it: Solmon et al. (2008) found that the EHP mechanism in western Africa induced by the dust diabatic warming (shortwave radiation absorption by dust) caused an increase in precipitation in Northern Sahel-Southern Sahara band. Lau et al. (2009) revealed that the large-scale atmospheric feedback caused by dust aerosols can enhance rainfall and cloudiness over the West Africa/Eastern Atlantic ITCZ while suppressing rainfall over the West Atlantic/Caribbean. Zhao et al. (2012) showed dust accumulated over the west slope of the Rocky Mountains and Mexican Plateau absorbed the shortwave radiation and heated the atmosphere, resulting in an eastward migration of North America monsoon-driven moisture

* Corresponding author at: Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China.
E-mail address: han-yx66@126.com (Y. Han).

https://doi.org/10.1016/j.atmosres.2017.12.004
Received 1 September 2017; Received in revised form 5 December 2017; Accepted 11 December 2017
Available online 13 December 2017
0169-8095/

convergence over the west slope of the Mountains and increased precipitation by up to ~40% over the east slope of the Mountains. This indicates EHP also existed in North America. Kim et al. (2015) found a large amount of dust aerosols transported from West Asia and Middle East led to an increase in dust loading over the Arabian Sea and Northwestern India. They suggested that atmospheric heating over the Tibetan Plateau due to dust aerosols may lead to anomalous circulation and an amplification of the Indian summer monsoon response to ENSO forcing.

However, some researchers doubt EHP mechanism is lack of reliable observation supporting. Nigam and Bollasina (2010) claimed the warmer land surface and reduced local precipitation in May are associated with an increased dust loading in Indian subcontinent, and there is no EHP mechanism. Lau and Kim (2011) responded to Nigam, et al.'s doubt and claimed the decreased precipitation in abundant dust loading region can help aerosol accumulation. EHP is not only the forcing effect of aerosols on local environment, but also responsible to the entire Indian monsoon system with a large-scale nonlocal affection on circulation and precipitation. Vinoj et al. (2014) found a positive relationship between dust aerosol concentration and Indian monsoon precipitation within a short time. Dust aerosols over the North Africa, West Asia and Arabian region can drive large-scale convergence over North Africa and Arabian Peninsula region by heating the atmosphere, leading to increased moisture convergence and precipitation over the Indian region.

The desert region in Northwestern China is one of the most important sources of atmospheric dust in the world (Washington et al., 2003; Zhang et al., 2003; Prospero et al., 2002). Dust aerosols from these regions greatly increase the dust aerosol concentration in Eastern China and the North Pacific via long-distance transport, thus affect air quality and marine ecosystems (Zhang, 2007; Tao et al., 2012, 2013;Wang et al., 2015). Different from other dust source regions, geographical distribution of several major desert areas in Northwestern China are relatively complex. The total annual precipitation is below 50 mm in desert areas because the moisture from Pacific and Indian Ocean is almost dissipated in long-range transport (Han et al., 2008a, 2008b; Wang et al., 2012). Recent studies have focused on the effects of dust aerosols on the climate factors in central and Eastern China (Han et al., 2012; Sun et al., 2012), the existence of EHP in Northwestern China lack the corresponding research. Guo and Yin (2015) suggested that atmospheric feedback triggered by absorbing dust aerosols will enhance updraft around 40°N averaged between 100°E and 120°E during the summer (in JJA), but further study on the circulation over dust emission sources is missing, the influence of EHP effect in Northwestern China still be open.

Base on the process of saltation bombardment and aggregate disintegration, Shao established a dust emission scheme couples a physical based wind erosion scheme suitable for East Asia (Shao, 2001, 2004; Shao et al., 2011). In this paper, WRF-Chem model coupled with the Shao dust emission scheme was applied to simulate the variation in regional meteorological factor of Northwestern China during summer. A sensitivity test with increasing dust aerosol emission is used to investigate the influence of dust aerosols on the vertical temperature structure, revealing the influence mechanism of EHP in Northwestern China and interaction between dust and the atmospheric circulation.

2. Study areas and methods

2.1. Study areas

The study area is East Asia (8–52°N, 78–131°E), including China, Japan, and the Korean Peninsula. The box in Fig. 1 is the main desert area, which is located in 32–43°N, 80–113°E, containing at least 4 major deserts in Northwestern China such as Taklimakan, Badain Jaran and Tengger, and Qaidam, their desert area accounts for 80% of the total area of the Chinese desert. Taklimakan is the major dust source region in Northwestern China, surrounded on three sides by mountains. Qaidam, which is the highest in altitude, lies in the northern part of the Tibetan Plateau. Badain Jaran and Tengger provide the major dust emissions in Inner Mongolia, which is adjacent to the Qilian Mountains. We draw two vertical sections (line AB and line CD) to explore the vertical meteorological field over the dust source region.

2.2. Model description

The Weather Research and Forecasting (WRF v3.6.1) Model with Chemistry (WRF-Chem) (Grell et al., 2005; Fast et al., 2006; Skamarock et al., 2008) is applied to simulate the meteorological processes and aerosol cycle over East Asia during the summer (from June to August) of 2003–2012. A model domain (8–52°N, 78–131°E) with 222 × 184 grids and a horizontal grid spacing of 30 km is employed, where 33 vertical layers extended from the ground to 10 hPa. Cloud chemistry and aerosol wet deposition are parameterized using the Lin cloud microphysics scheme (Gustafson et al., 2007). Non-local turbulent fluxes in large-scale eddies are represented by using the YSU PBL scheme, combined with the Noah land-surface scheme and the Monin-Obukhov surface layer scheme (Alizadeh Choobari et al., 2012). The indirect effects of dust aerosols remain largely uncertain, so we only focused on the direct effects of dust aerosols. The rapid radiative transfer model (RRTMG) (Mlawer et al., 1997; Iacono et al., 2000) is used for both short wave and long wave radiation to simulate the direct effect of aerosols. The refractive index of dust is set to 1.55 + 0.006i, consistent with previous observations in East Asia (Wu et al., 2009; Liu et al., 2016). Anthropogenic emissions such as SO_2, NO_x, NH_3 and CO_2 are obtained from MEIC (Multi-resolution Emission Inventory for China), but biomass burning emissions are not considered.

Since the 1980's, a series of dust emission schemes simulating the global and regional dust episodes have developed, such as GOCART dust emission scheme (Ginoux et al., 2001), Shao dust emission scheme (Shao, 2001, 2004; Shao et al., 2011), and DUSTRAN dust emission scheme (Allwine et al., 2006; Shaw et al., 2008). Different dust emission schemes tend to cause significant difference in the simulation of the emission and spatial distribution of dust concentration (Zhao et al., 2006; Kang et al., 2011). Wu and Lin (2014) calculated the dust concentration on the dust storm episode of 19–22 April 2002 based on the meteorological observation data of East Asia. The calculation results are compared with the simulation results of using GOCART scheme and Shao scheme. For the GOCART scheme, the potential dust source of Southeastern Mongolia and Inner Mongolia mid-east region are not considered, and the small wind velocity threshold of dust and large dust emission region is likely to produce false simulated dust emission region. The wind velocity threshold in the Shao scheme is closer to the observed value, so the Shao scheme is more accurate in simulating the concentration and distribution of dust aerosols in East Asia (Wu and Lin, 2014).

In the Shao dust emission scheme, the vertical dust emission flux F is dependent on the streamwise saltation flux Q. Saltation is initiated as soon as the friction velocity u_* exceeds the threshold friction velocity u_*t for saltation. Dust aerosol particle size distribution is divided into 4 classes (1.95–2.5, 2.5–5, 5–10, 10–20 μm). The dust emission flux F of particles with diameter d_j caused by saltating grains with particle diameter of d_i is given by

$$F(d_j, d_i) = c_y \eta_{fj} \left[(1-\gamma) + \gamma \frac{p_m(d_j)}{p_f(d_j)} \right] \frac{Q(i)g}{u_*^2} (1+\sigma_m) \tag{1}$$

where c_y is an empirical coefficient, η_{fj} is the total dust fraction, p_m (d_j) and p_f (d_j) are the minimal and fully-dispersed particle size distributions, respectively. The σ_m is the bombardment efficiency, g is the gravitational acceleration, γ describes how easily aggregated dust is released and is a function of u_* and u_*t.

In this study, the original field (D1) is simulated by WRF-Chem